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SIMULATION STUDY OF THRUST VECTORING FOR AIR COMBAT MANEUVERING FOR A LIGHTWEIGHT FIGHTER-CLASS AIRCRAFT (U)

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SUMMARY

A simulation study has been conducted to examine the effects of thrust vectoring on the combat effectiveness of an aircraft having maneuvering performance representative of a lightweight fighter-class aircraft. Air Force and Navy pilots flew simulated one-on-one engagements between the basic (unvectored) aircraft and the modified aircraft with vectoring. Independent variables for the study were (1) maximum vector angle (15° or 30°), (2) inclusion of induced lift, and (3) an increment in aircraft weight, representing an installation penalty.

INTRODUCTION

In support of research related to advanced fighter technology the Langley differential maneuvering simulator (DMS) has been used to investigate the effects of advanced aerodynamic concepts and changes in aircraft performance parameters on the one-on-one close-in capability of fighter aircraft. Changes which have been investigated include thrust-weight ratio T/W, wing loading W/S, maximum lift coefficient $C_{L,max}$, thrust reversing, and thrust vectoring. Initial studies used a simulated F-4 aircraft as the baseline from which changes were made. References 1 to 3 present results from these studies. Subsequently, the investigation was extended using an advanced baseline configuration (ABC) aircraft. The hypothetical ABC aircraft was defined to have maneuvering performance representative of lightweight fighter technology.

One concept for improving the maneuverability of a fighter is thrust vectoring. A normal force can be developed proportional to the sine of the vector angle, while axial force decreases slowly as the cosine of the vector angle. In addition, studies (refs. 4 to 6) have shown that by employing a vectorable jet near the trailing edge of an airfoil, it is possible to obtain an additional component of lift due to increased circulation over the airfoil. This was investigated during the F-4 parametric study (ref. 3), and results showed that thrust vectoring, particularly with induced lift, could provide a significant improvement in maneuverability for the F-4.

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This report presents results from simulation of limited thrust vectoring on the ABC aircraft. The basic (nonvectored) ABC was flown against the ABC with vectoring. Several configurations of the modified ABC aircraft were tested to assess the influence, singly and in combination, of maximum vector angle (15° and 30°), induced lift, and a weight increment representing an installation penalty.

SYMBOLS

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

$C_{L,max}$	maximum lift coefficient
C_D	drag coefficient
$\bar{c}$	mean aerodynamic chord, m (ft)
D_{ram}	ram drag, N (lb)
$F_{D,i}$	induced drag force, N (lb)
$F_{L,i}$	induced lift force, N (lb)
$F_{X,i}, F_{Y,i}, F_{Z,i}$	component of induced force along X, Y, and Z body axis, respectively, N (lb)
g	acceleration due to gravity, 9.81 m/sec^2 (32.2 ft/sec^2)
h	altitude, m (ft)
K_j	multiplier used to simulate induced lift
L/D	lift-drag ratio
M	Mach number
P_S	specific excess power, m/sec (ft/sec)
$\bar{q}$	dynamic pressure, Pa (lb/ft^2)

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R range, m (ft)

S wing reference area, m^2 (ft^2)

T/W thrust-weight ratio

T_{gross} gross installed thrust, N (lb)

T_X, T_Y, T_Z component of thrust force along X, Y, and Z body axis, respectively, N (lb)

V airspeed, m/sec (ft/sec)

W weight, kg (lb)

α angle of attack, deg

ΔW weight increment, kg (lb)

λ line-of-sight angle, deg

λ_A attacker's line-of-sight angle, deg

λ_O opponent's line-of-sight angle, deg

θ_j thrust vector angle, deg

Subscript:

e elevation

Abbreviations:

ABC advanced baseline configuration

ACM air combat maneuvering

AML adaptive maneuvering logic

AMP aircraft maneuvering parameter

[redacted]

DMS differential maneuvering simulator

TED trailing edge (of surface) down

TEU trailing edge (of surface) up

TOA time on offense with advantage

A dot over a symbol denotes derivative with respect to time.

SIMULATED AIRCRAFT

The ABC aircraft is assumed to be a single-engine, fixed-wing fighter. The flight control system is assumed to consist of conventional aerodynamic controls (stabilator, ailerons, and rudder), speed brakes, and automatically scheduled leading- and trailing-edge maneuver flaps. The physical data for the ABC aircraft are given in table 1. The aerodynamic data, flight control system, flying qualities, and maneuvering performance of the ABC are presented in reference 7.

TABLE 1.- PHYSICAL CHARACTERISTICS OF SIMULATED AIRCRAFT

Wing span, m (ft)	9.45 (31)
Wing reference area, m^2 (ft^2)	25.55 (275)
Mean aerodynamic chord, m (ft)	3.05 (10)
Aspect ratio	3.5
Weight, kg (lb)	7712 (17 000)
Static margin	$0.06\bar{c}$
Aileron deflection, deg	±20
Stabilator deflection:	
TED, deg	7.5
TEU, deg	-24.0
Rudder deflection, deg	±25
Armament	4 AIM-9G missiles plus gun
Sea-level static thrust-weight ratio	0.94

Thrust Calculations

Data for installed gross thrust and ram drag at maximum, military, and idle throttle settings are defined for the ABC aircraft as functions of altitude and Mach number and are presented in reference 7.

The engine axis was assumed alined with the aircraft body axis. Components of thrust in body axes were computed as

$$T_X = T_{gross} \cos \theta_j - D_{ram}$$

$$T_Y = 0$$

$$T_Z = -K_j T_{gross} \sin \theta_j$$

where θ_j is the thrust vector angle, commanded by the pilot, and K_j is a multiplier used to simulate induced lift.

For thrust vectoring without induced lift, K_j equals 1; for thrust vectoring with induced lift, K_j equals 2. Thus, the induced lift was simulated as equal to the component of gross thrust along the Z body axis.

Configurations Tested

The advanced baseline configuration (ABC) aircraft was the reference aircraft. In all cases the basic ABC was flown against some variant. The variants were defined by three independent variables:

(1) Maximum thrust vector angle	0°, 15°, or 30°
(2) Weight increment	0, 227, 454, or 907 kg (0, 500, 1000, or 2000 lb)
(3) Induced lift	K_j = 1 or 2

Eight cases were flown. These are shown in table 2.

TABLE 2.- CONFIGURATIONS STUDIED

Case	Maximum θ_j, deg	Weight increment		Induced lift
		kg	lb	
1	0	0	0	No
2	30	0	0	Yes
3	30	454	1000	Yes
4	30	454	1000	No
5	15	0	0	Yes
6	15	227	500	Yes
7	30	907	2000	Yes
8	0	454	1000	No

A value of 30° was selected as the maximum thrust vector angle because it appeared to be a reasonable limit for current technology in augmented thrust vectoring. The weight

[redacted]

increments were chosen to represent possible weight increases associated with installation of a vectorable nozzle. A component of induced lift due to vectoring $(K_j = 2)$ was included in most cases because previous work (refs. 4 to 6) has demonstrated that this effect can be obtained through careful aircraft and propulsion design and integration.

The two cases without vectoring (cases 1 and 8 in table 2) repeat earlier studies. Case 1 represents the basic ABC and is a check case for equal aircraft. Case 8 investigates the effects of a weight increment on the basic ABC, and it permits direct comparison with vectoring results from case 4.

Performance

Figures 1 to 3 illustrate the effects of the independent variables on maneuvering performance in terms of maximum sustained horizontal turn rate and maximum load factor. Figures 1 and 2 show the sustained turn rate and maximum load factor at an altitude of 3048 m (10 000 ft) for the ABC aircraft with fixed 30° vectoring and 15° vectoring, respectively, compared with those for the ABC aircraft without thrust vectoring.

Vectoring reduces the aircraft net longitudinal thrust but provides a normal force (propulsive lift) proportional to the sine of the vector angle. At speeds at which the instantaneous load factor of the basic ABC aircraft is limited by lift $(C_{L,max})$ rather than by maximum g, vectoring increases the instantaneous load factor capability because the propulsive lift augments the aerodynamic lift.

Sustained load factor and sustained turn rate occur at the angle of attack (and lift) at which the thrust force balances the drag force $(P_S = 0)$. Because of the lower longitudinal thrust available, the sustained turn rate for the vectored aircraft always occurs at a lower angle of attack (and correspondingly lower drag) than for the basic ABC. At low speeds the sustained $(P_S = 0)$ turn rate occurs at a moderate lift-drag ratio ($L/D \approx 3.5$ at $M = 0.4$). As speed increases, L/D at $P_S = 0$ increases also ($L/D \approx 7.5$ at $M = 0.9$). Thus, the drag reduction required to balance the reduced longitudinal thrust of the vectored aircraft results in a greater sacrifice in aerodynamic lift as speed increases. At low speeds the propulsive lift from vectoring more than offsets the lift loss associated with the reduction in drag and angle of attack; thus, the vectored aircraft has better sustained turn rate capability than the basic ABC. As speed increases, the loss in lift can become greater than the propulsive lift, resulting in a sustained turn rate lower than that of the basic ABC.

Figure 3 shows the effect of altitude on the sustained turn rate and maximum load factor. Thrust vectoring still helps at the higher altitude but the maneuvering capability is lower at the higher altitude because of the lower dynamic pressure (less lift force) and lower engine thrust.

Figure 4 shows specific excess power at $M = 0.5$ and an altitude of 3048 m (10 000 ft) for the basic ABC and for the ABC with fixed 15° and 30° vectoring. Specific

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excess power is computed as

$$P_S = \left(T_X \cos \alpha + T_Z \sin \alpha - C_D \bar{q} S\right)\frac{V}{W}$$

The 30° vectoring case provides the highest maximum load factor, but it does so at the expense of P_S at cruise (1g) flight. The basic ABC has the highest P_S at 1g. Thus, thrust vectoring appears most useful for maneuvering flight at moderate and high load factors. At cruise or low load factors, thrust vectoring provides no apparent benefit.

Assumptions

In addition to the assumptions involved in simulating the ABC aircraft discussed in reference 7, several other assumptions were made for this study:

(1) No disturbing moments were generated by vectored thrust.

(2) The thrust could be vectored at all throttle settings, including afterburning.

(3) Thrust recovery was negligible. Reference 6 has shown that, depending upon airspeed and airfoil section, it is possible to recover a substantial part of longitudinal thrust lost by vectoring. However, no attempt was made to model this phenomenon.

(4) Thrust loss from installation of vectored nozzle was negligible. These losses, estimated at 2 to 5 percent of the gross thrust, were neglected in the simulation because such a loss might be offset by a thrust recovery, which also was not simulated, and previous studies (ref. 1) have indicated that a 5-percent thrust loss or increase would not be apparent to the pilot or in the resulting DMS data.

(5) The additional lift which may be induced by thrust vectoring can be represented as an additional component perpendicular to the body axis for this study. Experimental data in reference 4 show incremental gain factors (ratio of induced lift to propulsive lift) of 1.0 to 3.0 for vector angles up to 45°; thus, the gain factor of unity assumed for the simulation appears conservative. Simulating the induced force as acting along the Z body axis is also conservative because it gives a smaller component (by the cosine of α) of lift, plus a small component of drag. The induced force $\left(\text{when } K_j = 2\right)$ in the body axis system is

$$F_{X,i} = F_{Y,i} = 0$$

$$F_{Z,i} = -T_{gross} \sin \theta_j$$

Corresponding lift and drag forces $F_{L,i}$ and $F_{D,i}$ are

$$F_{L,i} = -F_{Z,i} \cos \alpha = T_{gross} \sin \theta_j \cos \alpha$$

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$$F_{D,i} = -F_{Z,i} \sin \alpha = T_{gross} \sin \theta_j \sin \alpha$$

It is worth noting that at $\theta_j = 15^o$ and $\alpha = 10^o$, the drag force is 4.5 percent of the gross thrust or about the level proposed for installation losses. At $\theta_j = 30^o$ or higher angles of attack, the drag would be higher.

SIMULATION FACILITY

A schematic of the differential maneuvering simulator (DMS) is shown in figure 5. The system consists of (1) two 12.2-m-diameter (40 ft) projection spheres, each housing a cockpit and Earth-sky and target projection systems, (2) two target image generation systems, and (3) a control console for monitoring and interfacing the system drive signals with the Control Data 6600 computer system.

Each cockpit (fig. 6) has (1) a simplified instrument panel with the principal flight instruments (airspeed, altitude, load factor, attitude, etc.), (2) a lead-computing gunsight with range analog, (3) programmable hydraulic-driven control stick and rudder pedals, (4) throttle and speed-brake controls, and (5) a cockpit buffet system. Additional cues are added to assist the pilot in the operation of the simulator. A sound system supplies aerodynamic, engine, and weapon system noises. A separate audio system supplies a frequency-coded aural tone to indicate high angles of attack. The Earth projector does not indicate altitude changes; therefore, below an altitude of 1524 m (5000 ft) a light behind the pilot's head blinks with increasing frequency as the ground is approached. The system included a programmable valve which allows inflation of the pilot's anti-g garmet to offer a g cue to the pilot. To simulate the tendency of the pilot to black out at high g, the projection lights and cockpit instruments are dimmed as a function of time at high g. A more detailed description of the hardware is included in references 1 and 8.

SIMULATION PROCEDURE

The basic ABC aircraft was flown against the eight configurations described in table 2. For the study it was assumed that both aircraft (basic ABC and opponent) carried four AIM-9G missiles and a gun. Engagements started with the aircraft head-on with a separation of 2 n. mi. at an altitude of 4572 m (15 000 ft) and a Mach number of 0.9. The ground rules for the engagements were as follows:

(1) Both aircraft were to attempt to employ their weapons by using the best maneuvers for their aircraft system.

(2) No weapons would be employed on the first pass.

(3) All data runs lasted 3 min. Any run which ended earlier because of impacting the ground was recorded but was not used for data.

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Four combat-qualified pilots, two from the U.S. Navy and two from the U.S. Air Force, participated in the study. For each case (table 2) each pilot flew two engagements against each of the other three pilots in each aircraft, giving a total of 24 data runs per case. Before a case was flown, the pilots were briefed on the capabilities of the two simulated aircraft using information like that in figures 1 to 4 and reference 7. Before taking data, the pilots were given as much time as they desired to develop maneuvers and become familiar with the aircraft. This generally required 1 to 4 hours for each case.

Vectoring was simulated by using the outside throttle lever in the DMS cockpit to command thrust and the inside throttle lever to command vector angle. The angle varied linearly from $\theta_j = 0^\circ$ for inboard lever full forward to the maximum vector angle $\left(\theta_j = 0^\circ,\ 15^\circ,\ \text{or}\ 30^\circ\right)$ at full aft throttle. A cockpit instrument displayed the thrust vector angle to the pilot.

ANALYSIS AND SCORING

Several different criteria were used to evaluate the outcome of simulated engagements. These are described in references 9 and 10 and include (1) time on offense with advantage, (2) probability of gun conversion, (3) time in gun zone, (4) adaptive maneuvering logic (AML) value, and (5) missile launch opportunities, launches, and successes. Each of these is discussed in the following sections.

Time on Offense With Advantage

Time on offense with advantage (TOA) for an aircraft is defined as the time that the aircraft is behind the opponent (the opponent's line-of-sight angle λ_O exceeds 90°) and the opponent is in front of the aircraft (the attacker's line-of-sight angle λ_A is less than 90°). The line-of-sight angle λ is defined as the angle between the X body axis and the line-of-sight vector to the other aircraft. Time on offense with advantage provides a quantitative measure of aircraft capability and in previous studies (refs. 1 to 3) has correlated well with pilot opinion and other quantitative measures.

Probability of Gun Conversion and Time in Gun Zone

An aircraft was assumed to have achieved a gun conversion during a run when (1) range was less than 914 m (3000 ft), (2) the aircraft line-of-sight angle λ_A was less than 10°, and (3) the opponent's line-of-sight angle λ_O exceeded 120°. Time in gun zone was the total time that the aircraft satisfied the preceding criteria. Probability of conversion was computed as the number of engagements in which a conversion occurred divided by the total number of engagements (24).

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AML Value

The AML value is based on a quantitative criteria used by the Langley Adaptive Maneuvering Logic (AML) computer program. This program (ref. 10) is a digital model of a one-on-one air combat engagement. The program can be run in an off-line (batch) mode, or the decision and maneuvering logic can be used to supply a computer-driven opponent for a pilot in the DMS. The decision logic in the program tries to adaptively improve the AML value, which is calculated based on the questions in table 3. If an aircraft (assumed to be the attacker) can answer a question positively, a one is assigned; if not, a zero is assigned. The AML value is just the sum of the 11 values.

For each simulated engagement the AML value was computed for each aircraft every 0.5 sec and then averaged over the time of the engagement (3 min). Previous studies have shown that a difference of 1.0 in AML values indicates a definite aircraft superiority.

TABLE 3.- QUESTIONS USED TO ASSIGN AML VALUE

Question	Criteria (a)
1. Is opponent ahead of attacker?	$\lambda_A < 90^o$
2. Is attacker behind opponent?	$\lambda_O > 90^o$
3. Can attacker see opponent?	$-30^o < \lambda_{A,e} < 150^o$
4. Is opponent unable to see attacker?	$\lambda_{O,e} > 150^o$ or $\lambda_{O,e} < -30^o$
5. Is attacker in volume behind opponent?	$(\lambda_O > 150^o$ and $R < 914$ m$)$ or $(\lambda_O > 135^o$ and 914 m $< R < 1524$ m$)$
6. Is opponent outside of volume behind attacker?	$(R > 1524$ m$)$ or $(\lambda_A < 150^o$ if $R < 914$ m$)$ or $(\lambda_A < 135^o$ if 914 m $< R < 1524$ m$)$
7. Can attacker fire at opponent?	$\lambda_A < 30^o$ and $R < 914$ m
8. Is opponent unable to fire at attacker?	$\lambda_O > 30^o$ or $R > 914$ m
9. Are aircraft closing slowly?	-91 m/sec $< \dot{R} < 0$
10. Is attacker deviation angle below 60^o?	$\xi_A < 60^o$
11. Is attacker line-of-sight angle decreasing?	$\dot{\lambda}_A < 0^o$/sec

[a] 914 m = 3000 ft; 1524 m = 5000 ft; and -91 m/sec = -300 ft/sec.

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The elevation component of the attacker's line-of-sight angle $\lambda_{A,e}$ is measured from the X-Y plane of his body axes to the opponent's center of gravity (positive upward). The deviation angle ξ_A is defined as the angle between the attacker's velocity vector and the line-of-sight vector to the opponent.

Missile Analysis

The pilot's ability to achieve a missile launch opportunity and then to successfully launch the missile was analyzed by two methods.

The first method employs a postflight computer program to determine missile launch opportunities. The program compares the recorded trajectory information from the simulator with precalculated envelopes (launch acceptability regions) for the AIM-9G missile involving range, target aspect, off-boresight angle, maximum tracking rate, altitude, and Mach number, plus delays for sensor acquisition and lock-on. For example, the program requires that the attacker's line-of-sight angle λ_A be less than 30° for 3.5 seconds for acquisition, and less than 20° for an additional 1.5 seconds for lock-on before launch. If all the constraints are satisfied the program assumes that the missile can be launched and will impact. Up to four launch opportunities are allowed per engagement for each aircraft.

The second method involves a subprogram in the real time simulation program which "launches" and "flies" the AIM-9G missile when the pilot has a missile selected and pulls the trigger. In addition, the following cues are supplied in the DMS: (1) The pilot is given an aural tone whenever $\lambda_A < 20^{\circ}$, (2) the pilot in the target aircraft sees a flashing light under the wing of the attacking aircraft while the missile is in flight, and (3) the pilot in the attacking aircraft sees the target aircraft image "bloom" on missile impact. Some of the current limitations of the on-line missile program are (1) only one missile can be in flight at a time since the program disregards trigger pulls while a missile is in flight, and (2) a missile is assumed to be successful (impact) if it closes to within 10 m (32.8 ft) of the target inasmuch as no calculations of weapons effects or vulnerability are made.

Neither of the missile programs is completely realistic. Each has particular advantages and disadvantages. The postflight program includes time delays for sensor acquisition and lock-on but does not consider postlaunch maneuvers. The on-line program has no time delays, but realistically flies the missile against the maneuvering target. Thus, the successful launches indicated by the two programs would not necessarily be the same, and a completely realistic program which included delays and postlaunch maneuvering plus sensor characteristics might show even fewer successful launches.

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RESULTS

For each case studied, the average time on offense with advantage and the AML value were computed by averaging over the total number of runs (24) flown. Time in gun zone was averaged over the number of runs in which a gun conversion occurred. Probability of gun conversion was computed as the fraction of the runs in which a conversion occurred. The number of missile launch opportunities was the total for the 24 runs (with a maximum of four per run per aircraft) as determined by the off-line (postflight) program. The number of missile launches and impacts was the total number of trigger pulls and successful launches, respectively, as determined by the on-line (real time) program.

Basis for Comparison

All the data discussed previously are presented for each case studied. However, in comparing different cases, more emphasis is placed on TOA, gun conversion, and AML value than on missile results. There are two reasons for this. First, previous studies (refs. 2 and 3) have shown good correlation between TOA, probability of conversion, and AML value, and also with pilot opinion. Second, the number of successful missile launches (either opportunities or impacts) was generally so inconsistent as to make comparisons between cases difficult. Frequently, a pilot could achieve an offensive position at close range but was unable to successfully employ a missile. This occurred because of the nature of the engagements. Instead of a medium range intercept or pursuit, the engagements were characterized by hard maneuvering at low speed and close range. This generated high line-of-sight rates, which made it difficult for sensors to hold lock, and the engagements often occurred at ranges inside the minimum range of the AIM-9G.

Equal Aircraft

The first study conducted was a set of simulated engagements between equal ABC aircraft (case 1 in table 2). Table 4 summarizes the results with each DMS cockpit treated as a separate aircraft (denoted A and B).

TABLE 4.- RESULTS FOR EQUAL AIRCRAFT

Scoring criteria	A	B
Average TOA at 180 sec	36.9	50.6
Probability of gun conversion	6/24	4/24
Average time in gun zone, sec	7.6	1.0
Average AML value	5.1	5.3
Number of launch opportunities (off-line)	0	3
Number of missile launches (on-line)	8	13
Number of impacts (on-line)	1	3

Since the aircraft definition and simulator cockpits were identical, the difference in results is considered to be due to the pilots and the way they flew the aircraft. The data in table 4 show that in most of the runs neither aircraft was able to achieve a gun conversion. The difference in AML values is not significant. Pilots flying in cockpit B did somewhat better in achieving successful missile launches but did somewhat poorer in reaching the gun zone.

30° Vectoring With Induced Lift

Three sets of simulated engagements were made with one aircraft having a 30° vectoring capability plus induced lift. The three sets (cases 2, 3, and 7 in table 2) involved weight increments of 0, 454, and 907 kg (0, 1000, and 2000 lb). Results for the aircraft without a weight increment (case 2) are summarized in table 5.

TABLE 5.- RESULTS FOR BASIC ABC AIRCRAFT FLOWN AGAINST ABC AIRCRAFT WITH $\theta_j = 30^{\circ}$ AND $\Delta W = 0$

Scoring criteria	Basic ABC	Modified ABC
Average TOA at 180 sec	8.1	95.0
Probability of gun conversion	2/24	20/24
Average time in gun zone, sec	1.5	11.2
Average AML value	4.2	6.5
Number of launch opportunities . . .	0	9
Number of missile launches	1	34
Number of impacts	0	10

Table 5 indicates that the ABC with 30° vectoring capability, induced lift, and without a weight increase was overwhelmingly superior to the basic ABC. One question raised by the results is how much could the aircraft weight be increased and still remain superior to ABC. An attempt was made to answer this question by adding increments of 454 kg (1000 lb) and 907 kg (2000 lb) to the basic weight (7712 kg (17 000 lb)) of the vectored ABC. These results are presented in table 6 (case 3) and in table 7 (case 7).

The results for the vectored aircraft with a weight increment of 454 kg (1000 lb) (table 6) are nearly the same as the results for the aircraft with no increment (table 5). The only noticeable differences were the number of missile impacts and launch opportunities. Although the vectored aircraft was clearly superior to the basic ABC, the number of successful launch opportunities and impacts was small, illustrating the inconsistancy of the missile results.

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TABLE 6.- RESULTS FOR BASIC ABC AIRCRAFT FLOWN AGAINST ABC AIRCRAFT WITH $\theta_j = 30^o$ and $\Delta W = 454$ kg (1000 lb)

Scoring criteria	Basic ABC	Modified ABC
Average TOA at 180 sec	11.7	94.7
Probability of gun conversion	2/24	17/24
Average time in gun zone, sec	1.2	13.6
Average AML value	4.2	6.4
Number of launch opportunities	0	0
Number of missile launches	2	28
Number of impacts	2	3

TABLE 7.- RESULTS FOR BASIC ABC AIRCRAFT FLOWN AGAINST ABC AIRCRAFT WITH $\theta_j = 30^o$ AND $\Delta W = 907$ kg (2000 lb)

Scoring criteria	Basic ABC	Modified ABC
Average TOA at 180 sec	27.0	61.6
Probability of gun conversion	1/24	10/24
Average time in gun zone, sec	3.5	10.4
Average AML value	4.7	5.6
Number of launch opportunities	1	2
Number of missile launches	7	22
Number of impacts	3	8

The data in table 7 show that increasing the aircraft weight by 907 kg (2000 lb) (a 12-percent increase) reduced the vectored aircraft's superiority, but it still remained superior to the basic ABC. The difference in TOA and AML values is much smaller than in tables 5 and 6, and there were many engagements in which neither aircraft achieved a gun conversion.

30^o Vectoring Without Induced Lift

To examine the effect of the induced lift, a set of engagements was run with the modified aircraft having a weight increment of 454 kg (1000 lb) and a 30^o vectoring capability but with no induced lift. Table 8 presents the results for the aircraft operating under these conditions (case 4 in table 2).

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TABLE 8.- RESULTS FOR BASIC ABC AIRCRAFT FLOWN AGAINST ABC AIRCRAFT WITH $\theta_j = 30^{\circ}$, $\Delta W = 454$ kg (1000 lb), AND WITHOUT INDUCED LIFT

Scoring criteria	Basic ABC	Modified ABC
Average TOA at 180 sec	26.4	72.7
Probability of gun conversion	3/24	12/24
Average time in gun zone, sec	5.0	6.5
Average AML value	4.7	5.7
Number of launch opportunities	0	3
Number of missile launches	3	20
Number of impacts	0	7

The results in table 8 show that the vectored aircraft with a weight increment of 454 kg (1000 lb) and a 30° vectoring capability but without induced lift was still clearly superior to the basic ABC. However, comparison with table 6 shows that the lack of induced lift did reduce the level of superiority or advantage achieved.

Weight Increment Without Vectoring

Since the ABC aircraft with 30° vectoring was still superior, even with a weight increment of 454 kg (1000 lb) and without the induced lift, another set of engagements was flown without any vectoring but with the weight increment. These engagements (case 8 in table 2) might indicate whether the pilots or simulator were inadvertently biasing the results in favor of the modified aircraft. Also, case 8 had been run several months earlier with a different group of pilots during a study of the sensitivity of aircraft capability to weight changes. These earlier engagements were flown before the missile programs were operational, but the other scoring criteria were available for comparison. Table 9 presents the results for both pilot groups.

The aircraft with the weight increment was inferior to the basic ABC since it had no compensating advantage such as vectoring. The results for the two pilot groups are similar. If anything, the current group of pilots performed better in the basic ABC aircraft than the previous group.

TABLE 9.- RESULTS OF BASIC ABC AIRCRAFT FLOWN AGAINST ABC AIRCRAFT WITH $\theta_j = 0^o$ AND ΔW = 454 kg (1000 lb)

Scoring criteria	Present study		Previous study	
	Basic ABC	Modified ABC	Basic ABC	Modified ABC
Average TOA at 180 sec	77.9	25.5	65.4	28.1
Probability of gun conversion	9/24	3/24	11/24	6/24
Average time in gun zone, sec	15.1	8.7	15.1	2.8
Average AML value	5.7	4.6	5.8	4.7
Number of launch opportunities	0	0	-----	----
Number of missiles launched	21	4	-----	----
Number of impacts	3	1	-----	----

15^o Vectoring With Induced Lift

Two sets of engagements were flown with the modified aircraft having induced lift but with the vector angle limited to 15^o. One set (case 5 in table 2) was run without a weight increment; the other set (case 6 in table 2) was run with a weight increment of 227 kg (500 lb). Table 10 (case 5) and table 11 (case 6) summarize the results.

TABLE 10.- RESULTS FOR BASIC ABC AIRCRAFT FLOWN AGAINST ABC AIRCRAFT WITH $\theta_j = 15^o$ AND $\Delta W = 0$

Scoring criteria	Basic ABC	Modified ABC
Average TOA at 180 sec	16.8	87.4
Probability of gun conversion	1/24	16/24
Average time in gun zone, sec	0.5	17.7
Average AML value	4.2	6.3
Number of launch opportunities	0	0
Number of missiles fired	1	19
Number of impacts	0	5

TABLE 11.- RESULTS FOR BASIC ABC AIRCRAFT FLOWN AGAINST ABC AIRCRAFT WITH $\theta_j = 15^\circ$ AND $\Delta W = 227$ kg (500 lb)

Scoring criteria	Basic ABC	Modified ABC
Average TOA at 180 sec	14.2	81.7
Probability of gun conversion	0	14/24
Average time in gun zone, sec	0	10.1
Average AML value	4.4	6.1
Number of launch opportunities	0	3
Number of missiles fired	2	15
Number of impacts	0	5

The results in tables 10 and 11 indicate that a weight increment of 227 kg (500 lb) did not significantly affect the outcome of the engagements. The results show some loss of superiority compared with the aircraft having 30° vectoring and induced lift (tables 5 and 6), but the loss is small, indicating that most of the advantage could be realized with the smaller vector angle.

Average Flight Conditions

Time histories of engagements were examined to determine the conditions under which thrust vectoring was used. Percentages of total run time and time on offense with advantage (TOA) were computed for several Mach-number, angle-of-attack, and vector-angle intervals. These are presented in appendix A. The time on offense with advantage is summarized in figures 7 to 9 for the vectored aircraft with induced lift (cases 2, 3, and 5 to 7 in table 2).

Figure 7 indicates that most of the TOA occurred at low speeds. After the initial pass at $M = 0.9$ both aircraft tried to make the quickest, tightest turn by slowing down to near corner velocity (minimum speed for maximum load factor) and then pulling near maximum load factor. This was followed by hard maneuvering to try to reach an advantageous position and to prevent the opponent from gaining an advantage. During this hard maneuvering both aircraft lost energy, and the engagement descended to low speeds ($M < 0.6$) and low altitude ($h < 3$ km). This was to the advantage of the aircraft with thrust vectoring since, as was seen earlier, the simulated thrust vectoring was most useful at lower speeds where the normal force due to vectoring and induced lift could augment the lift of the wing. Table 12 repeats table 2 and shows the average Mach number for each case. It is interesting to note that in every case the inferior aircraft had the higher average speed, indicating that the pilot was trying to keep the speed up to maintain energy and operate in a region where thrust vectoring was less effective.

TABLE 12.- AVERAGE MACH NUMBER FOR EACH CASE FOR CONFIGURATIONS STUDIED

Case	Modified aircraft					Average Mach number for basic ABC
	Maximum vector angle	Weight increment		Induced lift	Average Mach number	
		kg	lb			
1	0	0	0	No	0.44	0.44
2	30°	0	0	Yes	.38	.50
3	30°	454	1000	Yes	.37	.54
4	30°	454	1000	No	.37	.48
5	15°	0	0	Yes	.33	.40
6	15°	227	500	Yes	.36	.44
7	30°	907	2000	Yes	.36	.53
8	0	454	1000	No	.48	.42

Figure 8 shows that the TOA was about evenly divided between the three angle-of-attack intervals for the aircraft with 30° vectoring capability. The aircraft with 15° vectoring capability spent more time at higher angles of attack, probably because it required a higher angle of attack to achieve the same total lift as the aircraft with 30° vectoring.

Figure 9 shows that thrust vectoring was used extensively, but very little time was spent at intermediate vector angles. This is consistent with results of earlier simulations reported in reference 3.

Aircraft Maneuvering Parameter

One of the objectives of the previous studies has been to develop a function relating a scoring parameter, such as TOA, to aircraft capability. Such a function would make it possible to predict ACM outcome from basic aircraft characteristics. One such function being examined is the aircraft maneuvering parameter (AMP) described in reference 2, which relates TOA to the basic characteristics $\left(T/W,\ W/S,\ C_{L,max},\text{ and } L/D\right)$ of each aircraft.

[redacted]

The aircraft maneuvering parameter is used in the following manner:

(1) An AMP value is computed for each aircraft as

$$\text{AMP value} = \frac{\left[(T/W)(L/D)_{man}\right]^{1/3} C_{L,max}}{W/S}$$

where all conditions are referenced to $M = 0.8$ at an altitude of 3048 m (10 000 ft). The lift-drag ratio at maneuver conditions $(L/D)_{man}$ is assumed to be one-half of maximum L/D. Thrust vectoring capability is treated as an increase in $C_{L,max}$.

(2) The AMP ratio for each pair of competing aircraft is then computed. The AMP ratio for a particular aircraft is that aircraft's AMP value divided by the AMP value of the opponent. The AMP ratio of the opponent is the inverse. Thus, as one aircraft improved, the AMP ratio for the improved aircraft increases and, simultaneously, the AMP ratio for the opponent decreases. The AMP ratios for the aircraft in the eight cases studied are given in table 13.

TABLE 13.- AMP RATIOS FOR SIMULATED AIRCRAFT

Case (a)	AMP ratio	
	$\frac{\text{Modified}}{\text{Basic}}$ ABC	$\frac{\text{Basic}}{\text{Modified}}$ ABC
1	1.00	1.00
2	1.12	.89
3	1.04	.96
4	.98	1.02
5	1.06	.94
6	1.02	.98
7	.96	1.04
8	.93	1.08

[a]For description of the modified aircraft in these cases, see table 12.

(3) By knowing the AMP ratios and using the curve in figure 10, the nondimensional time on offense with advantage TOA/t can be predicted. The ratio TOA/t is the total TOA normalized by the total time of the engagement (t = 180 sec). The curve in figure 10 is based on a correlation of results from previous studies, discussed in reference 2. As noted in references 2 and 3, the results of previous studies, involving parametric changes in similar aircraft and simulated engagements between dissimilar aircraft, have agreed well with AMP.

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The points plotted in figure 10 show the results from the eight cases studied (table 12). The circles denote cases 1 and 8 in which the modified aircraft did not have thrust vectoring. The other symbols denote cases involving thrust vectoring. Solid symbols denote results for the basic ABC; open symbols denote results for the modified aircraft.

Results for the aircraft without thrust vectoring (cases 1 and 8) are in reasonable agreement with the AMP curve. Results for cases with thrust vectoring (cases 2 to 7) are not. In fact, the AMP value predicted that the basic ABC would be superior (having a higher AMP ratio) in cases 4 and 7, but the results show that the vectored aircraft remained clearly superior.

This disagreement between prediction and results may be the result of an effect that cannot be predicted with the simple AMP equation. Previous studies have shown a few situations in which the AMP equation cannot predict the outcome, notably, when competing aircraft have the same maneuvering performance but grossly different handling qualities or when one aircraft has a high deceleration capability, such as thrust reversing. The equation for the AMP value has no way of quantifying these effects. Work is continuing to refine the AMP and extend it to these areas, and this may improve the prediction for thrust vectoring also.

CONCLUDING REMARKS

A piloted simulation study of air combat maneuvering between aircraft having performance representative of lightweight fighter technology, in which one aircraft had simulated thrust vectoring capability, has been conducted, under the assumptions of (1) vectoring available at all thrust levels, (2) no disturbing moments, and (3) no gross thrust loss or recovery due to vectoring.

The limited thrust vectoring capability simulated (either 15° or 30°) provided a very significant advantage. Scoring parameters indicated the superiority of the aircraft with vectoring. The advantage obtained did not increase directly with vector angle capability. The increase in superiority at 30° vectoring over that obtained with 15° vectoring might not justify the additional weight and complexity associated with larger vector angles.

Induced lift, which was simulated as equal to the normal force due to vectoring, provided an increased advantage compared with the results obtained with vectoring but without induced lift.

Moderate weight increments (e.g., 454 kg (1000 lb) at 30° vectoring) had little effect on results for the aircraft with vectoring plus induced lift. Larger weight increments, or moderate increments without vectoring, did significantly reduce aircraft capability.

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Simulated engagements rapidly degraded from initial transonic speeds to low speeds and low altitude as the aircraft maneuvered for advantage. This tended to emphasize the advantage of vectoring, which was greatest at low-energy maneuvering conditions. Vectoring, as simulated, provided little or no benefit at high speed and cruise conditions.

One scoring parameter used in the study was the number of missile launch attempts and the number of successful simulated launches. Missile results were inconsistent. Relatively few missile launches were attempted by the pilots, and only a small percentage of these were successful. This may have occurred because engagements were frequently at close range, and pilots chose to maneuver for a gun firing position inside minimum missile range. The small number of successful missile shots with aircraft having such high performance suggests an area for future study.

The aircraft maneuvering parameter, which has satisfactorily predicted results for performance changes in previous studies, did not predict the results of cases involving thrust vectoring. Thrust vectoring provided more advantage than predicted, particularly with induced lift. The prediction was satisfactory for cases without thrust vectoring.

Very little time was spent at intermediate thrust vector angles (1/3 to 2/3 of maximum angle), indicating that pilots tended to operate at near zero or near full vectoring. This could be done easily, since no disturbing moments due to vectoring were simulated. Pilots learned quickly to use thrust vectoring and did use it much of the time.

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APPENDIX A

FREQUENCY DISTRIBUTION OF RUN TIME AND TIME ON OFFENSE WITH ADVANTAGE

Tables A2 to A13 show percentages of run time (180 sec) and time on offense with advantage (TOA) for various Mach-number, angle-of-attack, and vector-angle intervals for all modified aircraft. Table A1 shows the cases studied and the corresponding tables.

TABLE A1.- CASES STUDIED

Maximum θ_j, deg	ΔW		Induced lift	Table indicating percentage of –	
	kg	lb		Run time	TOA
30	0	0	Yes	A2	A8
30	454	1000	Yes	A3	A9
30	454	1000	No	A4	A10
15	227	500	Yes	A5	A11
15	0	0	Yes	A6	A12
30	907	2000	Yes	A7	A13

TABLE A2.- PERCENTAGE OF RUN TIME WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITH INDUCED LIFT AND $\Delta W = 0$

Angle of attack	Mach number	Percentage of run time within θ_j intervals of –		
		0° to 10°	10° to 20°	20° to 30°
$< 10^{\circ}$	< 0.4	5.98	0.22	11.60
	0.4 to 0.6	4.02	0.28	6.04
	0.6 to 0.8	1.81	0.07	1.99
	0.8 to 1.0	3.35	0	0.49
	> 1.0	0.29	0.02	0.13
10° to 20°	< 0.4	4.80	0.17	14.92
	0.4 to 0.6	2.36	0.11	6.12
	0.6 to 0.8	1.65	0.06	1.58
	0.8 to 1.0	1.17	0.01	0.56
	> 1.0	0	0	0.02
$> 20^{\circ}$	< 0.4	5.36	0.28	21.32
	0.4 to 0.6	0.38	0	2.83
	0.6 to 0.8	0	0	0.01
	0.8 to 1.0	0	0	0
	> 1.0	0	0	0

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TABLE A3.- PERCENTAGE OF RUN TIME WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITH INDUCED LIFT AND $\Delta W = 454$ kg (1000 lb)

Angle of attack	Mach number	Percentage of run time within θ_j intervals of –		
		0° to 10°	10° to 20°	20° to 30°
$< 10^\circ$	< 0.4	6.21	0.36	11.51
	0.4 to 0.6	4.21	0.18	3.38
	0.6 to 0.8	0.76	0.06	0.77
	0.8 to 1.0	3.35	0.05	0.49
	> 1.0	0.26	0.03	0.14
10° to 20°	< 0.4	6.84	0.52	13.14
	0.4 to 0.6	3.99	0.31	3.90
	0.6 to 0.8	1.91	0.02	1.05
	0.8 to 1.0	1.56	0.02	0.50
	> 1.0	0.03	0	0.03
$> 20^\circ$	< 0.4	5.86	0.46	23.09
	0.4 to 0.6	1.30	0.16	3.20
	0.6 to 0.8	0.19	0	0.11
	0.8 to 1.0	0.02	0	0
	> 1.0	0	0	0

TABLE A4.- PERCENTAGE OF RUN TIME WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITHOUT INDUCED LIFT AND $\Delta W = 454$ kg (1000 lb)

Angle of attack	Mach number	Percentage of run time within θ_j intervals of –		
		0° to 10°	10° to 20°	20° to 30°
$< 10^\circ$	< 0.4	6.23	0.23	5.22
	0.4 to 0.6	4.35	0.22	1.13
	0.6 to 0.8	2.76	0	0.20
	0.8 to 1.0	2.87	0.03	0.09
	> 1.0	0.59	.01	0.03
10° to 20°	< 0.4	7.11	0.61	8.12
	0.4 to 0.6	3.87	0.20	1.40
	0.6 to 0.8	3.33	0.01	0.34
	0.8 to 1.0	1.11	0	0.10
	> 1.0	0.23	0	0.01
$> 20^\circ$	< 0.4	13.57	1.40	28.04
	0.4 to 0.6	2.76	0.02	2.48
	0.6 to 0.8	0.78	0	0.20
	0.8 to 1.0	0.28	0.01	0.05
	> 1.0	0	0	0

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TABLE A5.- PERCENTAGE OF RUN TIME WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITH INDUCED LIFT AND ΔW = 227 kg (500 lb)

Angle of attack	Mach number	Percentage of run time within θ_j intervals of –		
		0° to 5°	5° to 10°	10° to 15°
$< 10^\circ$	< 0.4	4.91	0.13	6.57
	0.4 to 0.6	3.90	0.03	0.75
	0.6 to 0.8	1.54	0.01	0.10
	0.8 to 1.0	2.40	0.20	1.28
	> 1.0	0.07	0	0.10
10° to 20°	< 0.4	6.82	0.24	11.04
	0.4 to 0.6	5.55	0.26	1.68
	0.6 to 0.8	1.69	0.03	0.69
	0.8 to 1.0	0.87	0.08	0.93
	> 1.0	0.02	0	0
$> 20^\circ$	< 0.4	7.51	0.36	35.00
	0.4 to 0.6	2.05	0.08	1.78
	0.6 to 0.8	1.08	0	0.13
	0.8 to 1.0	0.11	0	0
	> 1.0	0	0	0

TABLE A6.- PERCENTAGE OF RUN TIME WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITH INDUCED LIFT AND ΔW = 0

Angle of attack	Mach number	Percentage of run time within θ_j intervals of –		
		0° to 5°	5° to 10°	10° to 15°
$> 10^\circ$	< 0.4	4.25	0.25	8.62
	0.4 to 0.6	3.60	0.01	1.11
	0.6 to 0.8	1.22	0.02	0.30
	0.8 to 1.0	2.79	0.06	0.54
	> 1.0	0	0	0
10° to 20°	< 0.4	5.37	0.26	13.34
	0.4 to 0.6	3.61	0.15	1.77
	0.6 to 0.8	1.01	0.02	0.68
	0.8 to 1.0	0.54	0	0.24
	> 1.0	0	0	0
$> 20^\circ$	< 0.4	3.86	0.29	40.43
	0.4 to 0.6	1.46	0.06	2.77
	0.6 to 0.8	0.84	0.01	0.23
	0.8 to 1.0	0.26	0	0.01
	> 1.0	0	0	0

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TABLE A7.- PERCENTAGE OF RUN TIME WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITH INDUCED LIFT AND ΔW = 907 kg (2000 lb)

Angle of attack	Mach number	Percentage of run time within θ_j intervals of –		
		0^o to 10^o	10^o to 20^o	20^o to 30^o
< 10^o	< 0.4	10.69	0.26	5.91
	0.4 to 0.6	6.74	0.05	0.96
	0.6 to 0.8	2.78	0.01	0.03
	0.8 to 1.0	3.01	0.03	0.11
	> 1.0	0.28	0	0
10^o to 20^o	< 0.4	10.13	0.34	6.33
	0.4 to 0.6	5.71	0.11	1.18
	0.6 to 0.8	2.69	0.03	0.28
	0.8 to 1.0	1.25	0	0.16
	> 1.0	0.14	0	0
> 20^o	< 0.4	10.52	0.41	23.26
	0.4 to 0.6	3.20	0.09	1.70
	0.6 to 0.8	1.02	0	0.16
	0.8 to 1.0	0.38	0	0.02
	> 1.0	0	0	0

TABLE A8.- PERCENTAGE OF TOA WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITH INDUCED LIFT AND ΔW = 0

Angle of attack	Mach number	Percentage of TOA within θ_j intervals of –		
		0^o to 10^o	10^o to 20^o	20^o to 30^o
< 10^o	< 0.4	3.97	0.22	13.10
	0.4 to 0.6	2.94	0.37	6.00
	0.6 to 0.8	1.96	0.02	1.45
	0.8 to 1.0	0.09	0	0.24
	> 1.0	0.02	0	0.02
10^o to 20^o	< 0.4	4.64	0.26	17.44
	0.4 to 0.6	2.20	0.13	7.58
	0.6 to 0.8	0.93	0.04	1.53
	0.8 to 1.0	0.13	0	0.09
	> 1.0	0	0	0
> 20^o	< 0.4	4.94	0.35	25.41
	0.4 to 0.6	0.43	0	3.48
	0.6 to 0.8	0	0	0.02
	0.8 to 1.0	0	0	0
	> 1.0	0	0	0

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TABLE A9.- PERCENTAGE OF TOA WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITH INDUCED LIFT AND ΔW = 454 kg (1000 lb)

Angle of attack	Mach number	Percentage of TOA within θ_j intervals of –		
		0° to 10°	10° to 20°	20° to 30°
< 10°	< 0.4	4.27	0.52	14.28
	0.4 to 0.6	2.79	.22	4.61
	0.6 to 0.8	0.30	0.04	0.56
	0.8 to 1.0	0.17	0	0.32
	> 1.0	0	0	0
10° to 20°	< 0.4	5.52	0.80	16.55
	0.4 to 0.6	3.34	0.24	3.75
	0.6 to 0.8	0.97	0.02	1.08
	0.8 to 1.0	0.17	0	0.19
	> 1.0	0.02	0	0.02
> 20°	< 0.4	5.07	0.71	27.88
	0.4 to 0.6	0.71	0.17	4.48
	0.6 to 0.8	0.04	0	0.13
	0.8 to 1.0	0	0	0
	> 1.0	0	0	0

TABLE A10.- PERCENTAGE OF TOA WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITHOUT INDUCED LIFT AND ΔW = 454 kg (1000 lb)

Angle of attack	Mach number	Percentage of TOA within θ_j intervals of –		
		0° to 10°	10° to 20°	20° to 30°
< 10°	< 0.4	6.04	0.31	6.43
	0.4 to 0.6	3.83	0.37	1.28
	0.6 to 0.8	1.05	0	0.20
	0.8 to 1.0	0	0	0
	> 1.0	0	0	0.03
10° to 20°	< 0.4	6.18	1.22	11.11
	0.4 to 0.6	2.44	0.31	1.62
	0.6 to 0.8	1.45	0	0.23
	0.8 to 1.0	0.20	0	0.03
	> 1.0	0	0	0
> 20°	< 0.4	11.37	1.39	35.91
	0.4 to 0.6	2.47	0.06	3.60
	0.6 to 0.8	0.65	0	0.17
	0.8 to 1.0	0.09	0	0
	> 1.0	0	0	0

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TABLE A11.- PERCENTAGE OF TOA WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITH INDUCED LIFT AND ΔW = 227 kg (500 lb)

Angle of attack	Mach number	Percentage of TOA within θ_j intervals of –		
		0^o to 5^o	5^o to 10^o	10^o to 15^o
$< 10^o$	< 0.4	4.73	0.10	6.50
	0.4 to 0.6	3.77	0.03	0.81
	0.6 to 0.8	1.39	0.03	0
	0.8 to 1.0	0.05	0	0.08
	> 1.0	0	0	0
10^o to 20^o	< 0.4	5.61	0.33	13.04
	0.4 to 0.6	4.83	0.33	1.62
	0.6 to 0.8	1.37	0	0.53
	0.8 to 1.0	0.18	0	0.61
	> 1.0	0	0	0
$> 20^o$	< 0.4	8.16	0.56	39.79
	0.4 to 0.6	2.35	0.13	2.33
	0.6 to 0.8	0.73	0	0
	0.8 to 1.0	0.05	0	0
	> 1.0	0	0	0

TABLE A12.- PERCENTAGE OF TOA WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITH INDUCED LIFT AND ΔW = 0

Angle of attack	Mach number	Percentage of TOA within θ_j intervals of –		
		0^o to 5^o	5^o to 10^o	10^o to 15^o
$< 10^o$	< 0.4	4.48	0.33	9.27
	0.4 to 0.6	2.78	0.02	1.01
	0.6 to 0.8	0.94	0	0.38
	0.8 to 1.0	0.24	0	0.07
	> 1.0	0	0	0
10^o to 20^o	< 0.4	6.32	0.26	15.43
	0.4 to 0.6	2.93	0.09	1.84
	0.6 to 0.8	0.59	0.02	0.50
	0.8 to 1.0	0.17	0	0.14
	> 1.0	0	0	0
$> 20^o$	< 0.4	4.62	0.21	41.45
	0.4 to 0.6	1.39	0.07	3.23
	0.6 to 0.8	0.80	0.02	0.19
	0.8 to 1.0	0.19	0	0
	> 1.0	0	0	0

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TABLE A13.- PERCENTAGE OF TOA WITHIN THRUST VECTOR INTERVALS FOR AIRCRAFT WITH INDUCED LIFT AND ΔW = 907 kg (2000 lb)

Angle of attack	Mach number	Percentage of TOA within θ_j intervals of –		
		0° to 10°	10° to 20°	20° to 30°
< 10°	< 0.4	10.19	0.40	8.75
	0.4 to 0.6	4.84	0.10	2.04
	0.6 to 0.8	0.53	0	0.03
	0.8 to 1.0	0.07	0	0.03
	> 1.0	0.03	0	0
10° to 20°	< 0.4	9.52	0.40	8.02
	0.4 to 0.6	6.01	0.17	1.74
	0.6 to 0.8	1.24	0.03	0.53
	0.8 to 1.0	0.17	0	0.03
	> 1.0	0.03	0	0
> 20°	< 0.4	8.78	0.60	27.76
	0.4 to 0.6	3.74	0.10	2.81
	0.6 to 0.8	0.73	0	0.37
	0.8 to 1.0	0.17	0	0.03
	> 1.0	0	0	0

[redacted]

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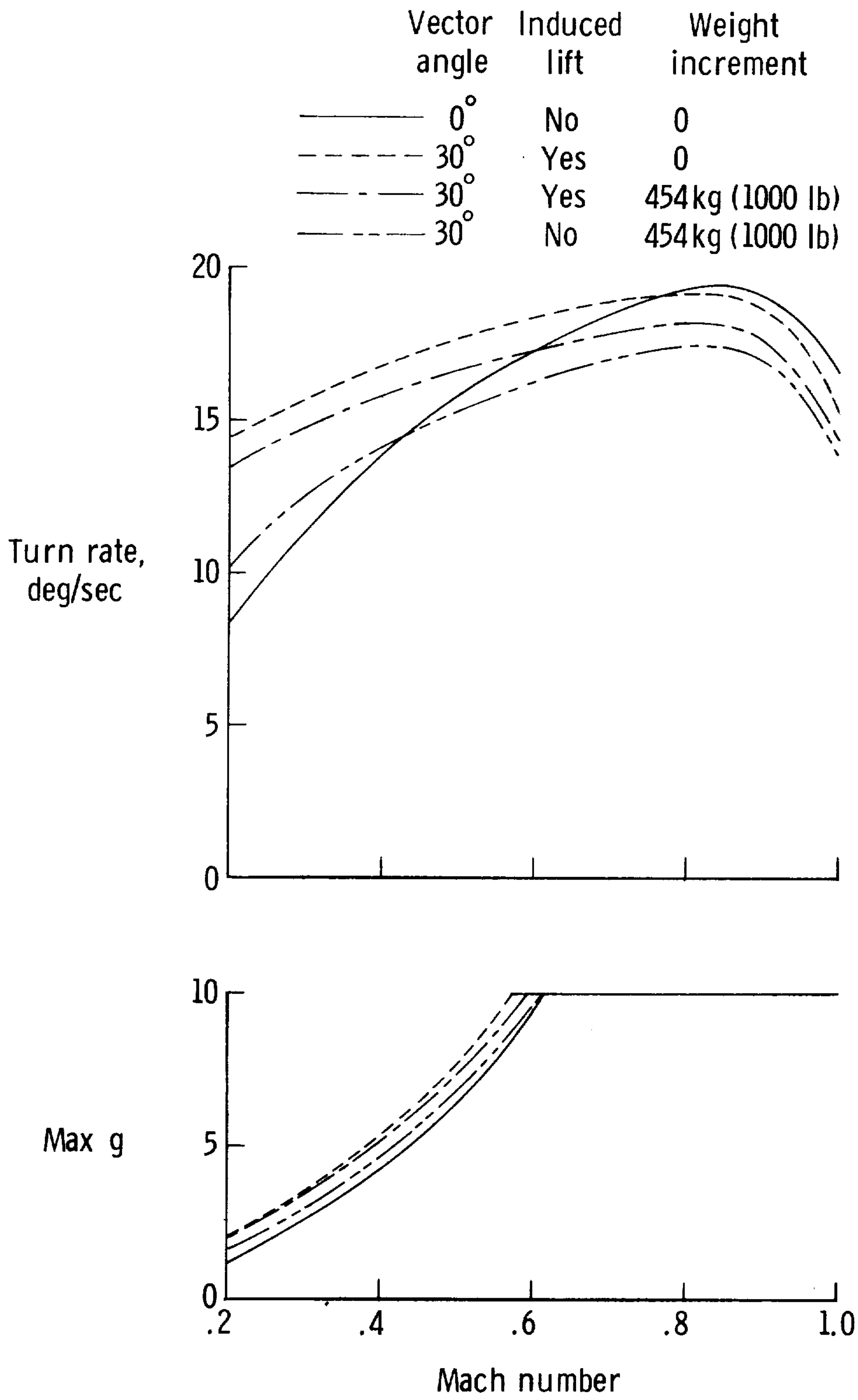

Figure 1.- Sustained turn rate and maximum load factor at altitude of 3048 m (10 000 ft) for aircraft with 30° vector angle.

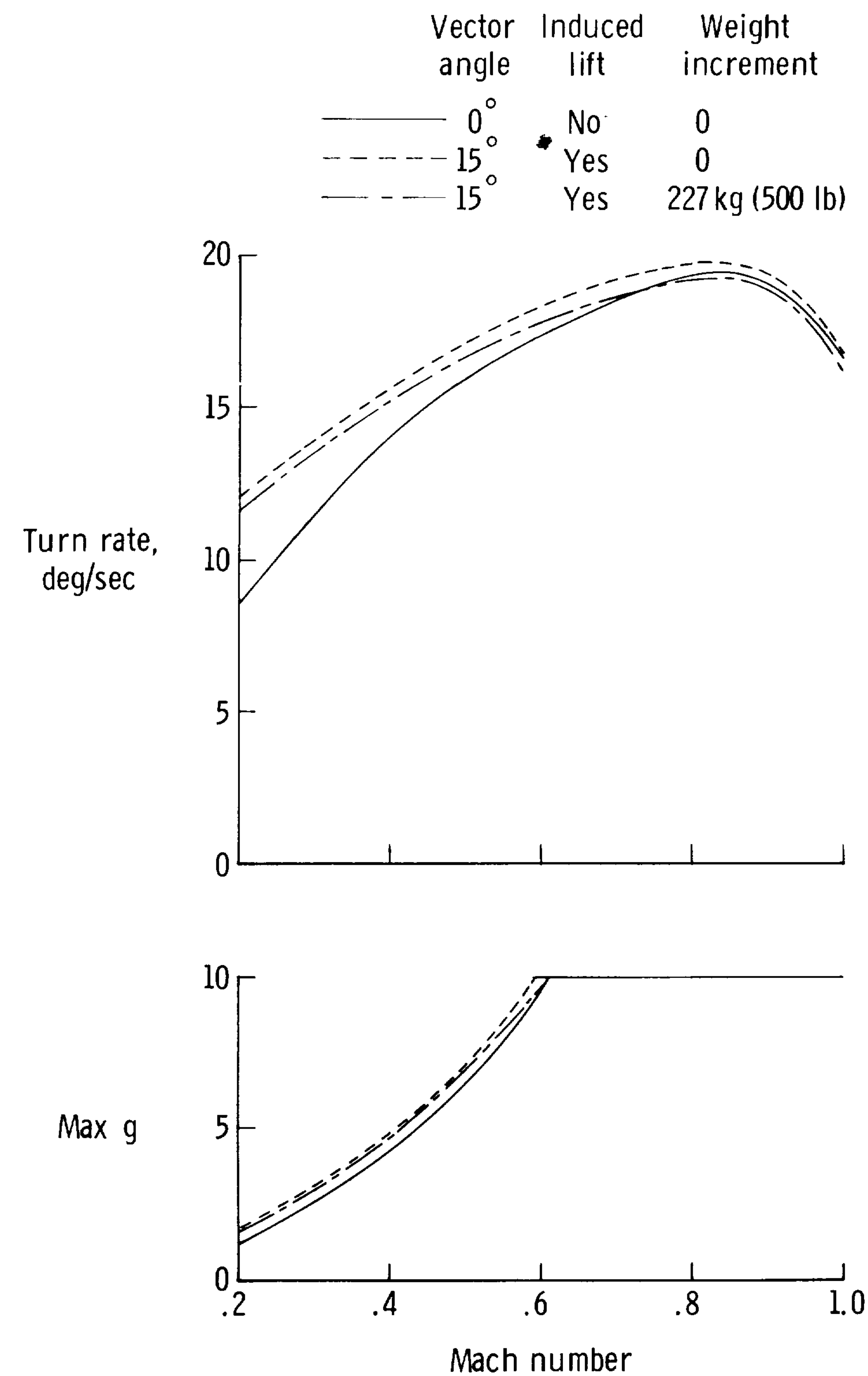

Figure 2.- Sustained turn rate and maximum load factor at altitude of 3048 m (10 000 ft) for aircraft with 15° vector angle.

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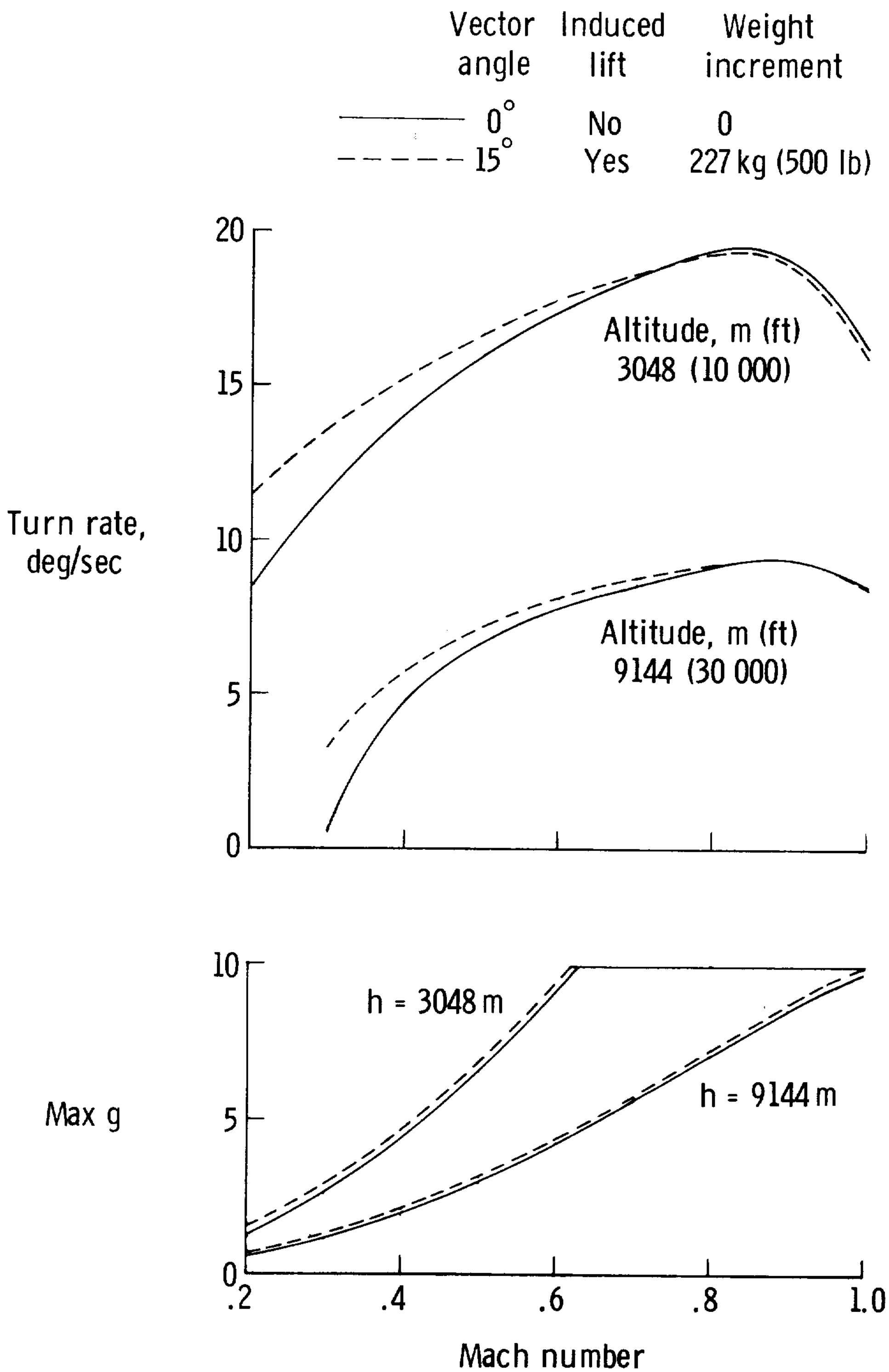

Figure 3.- Sustained turn rate and maximum load factor at altitudes of 3048 m (10 000 ft) and 9144 m (30 000 ft).

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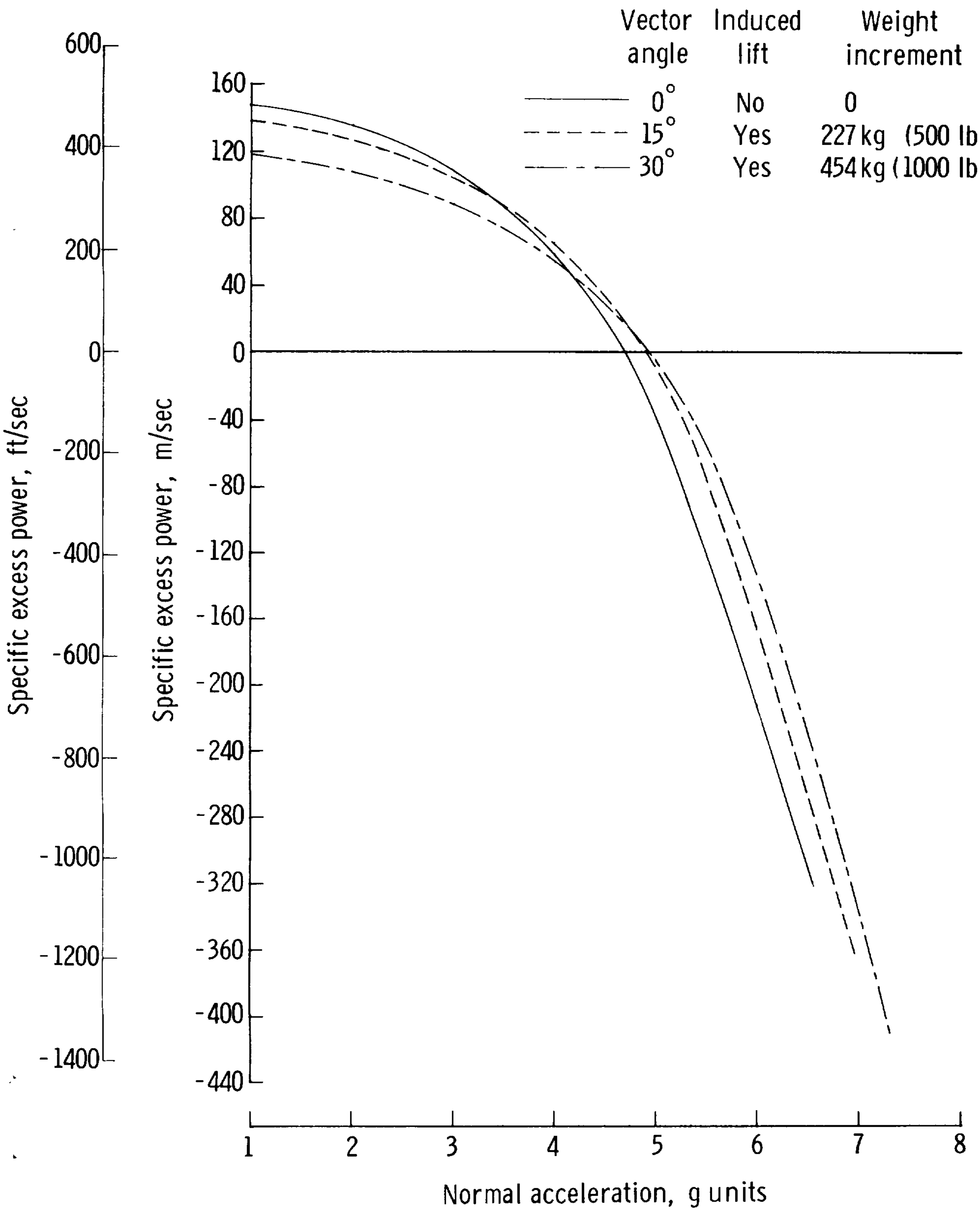

Figure 4.- Specific excess power at M = 0.5 and altitude of 3048 m (10 000 ft).

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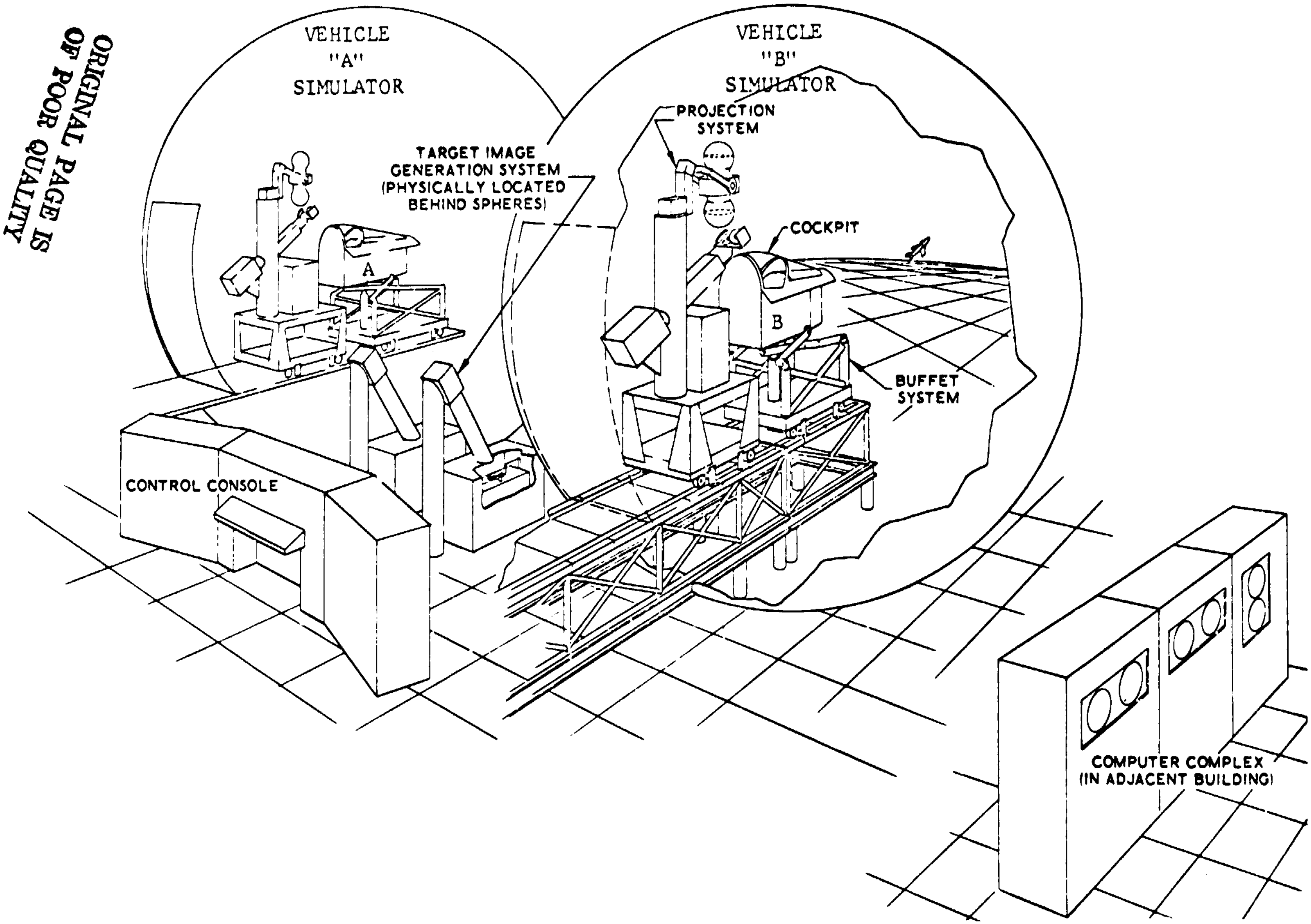

Figure 5.- Differential maneuvering simulator.

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Figure 6.- Differential maneuvering simulator cockpit.

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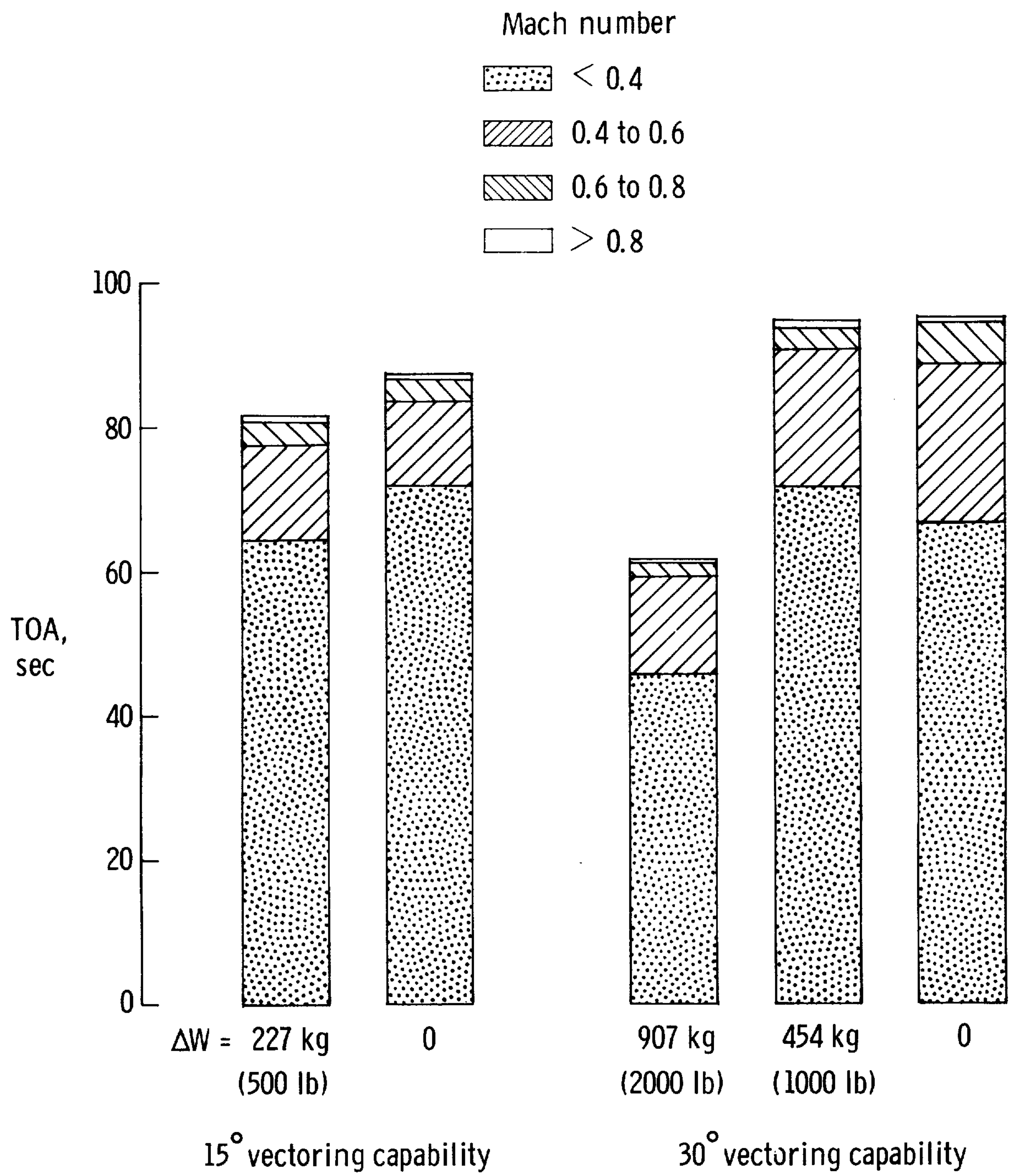

Figure 7.- Time on offense with advantage in Mach-number intervals.

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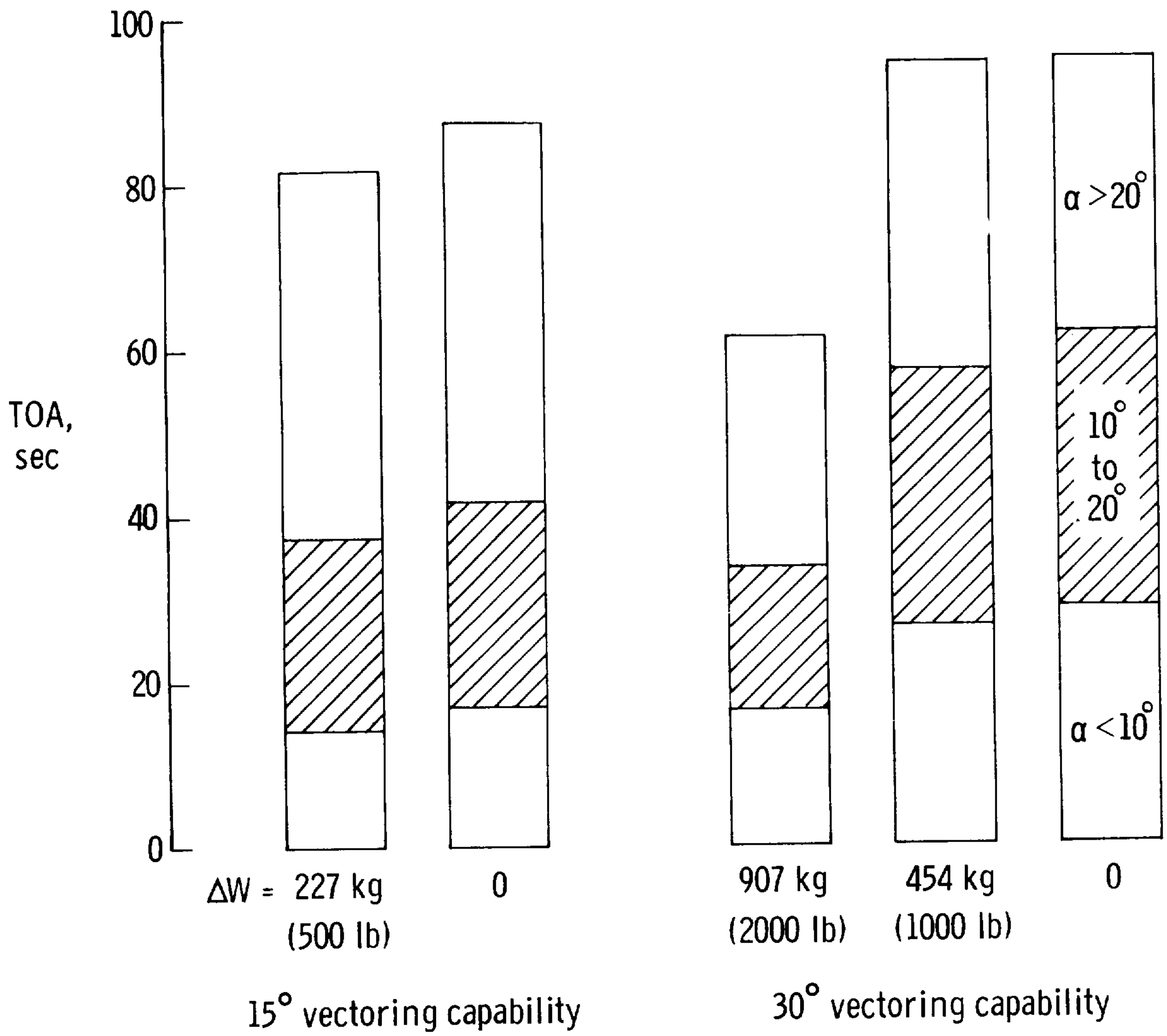

Figure 8.- Time on offense with advantage in angle-of-attack intervals.

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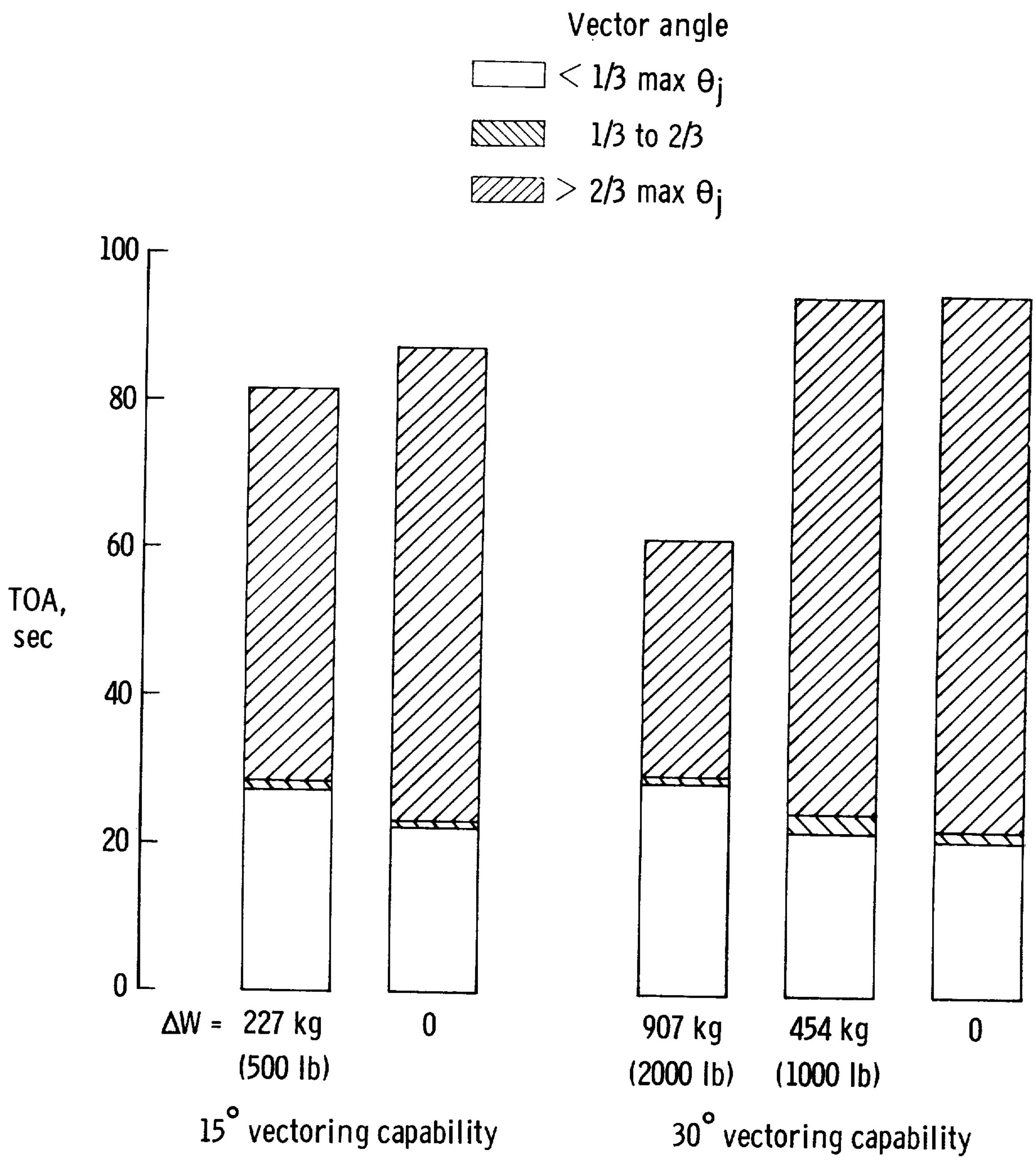

Figure 9.- Time on offense with advantage in thrust vector intervals.

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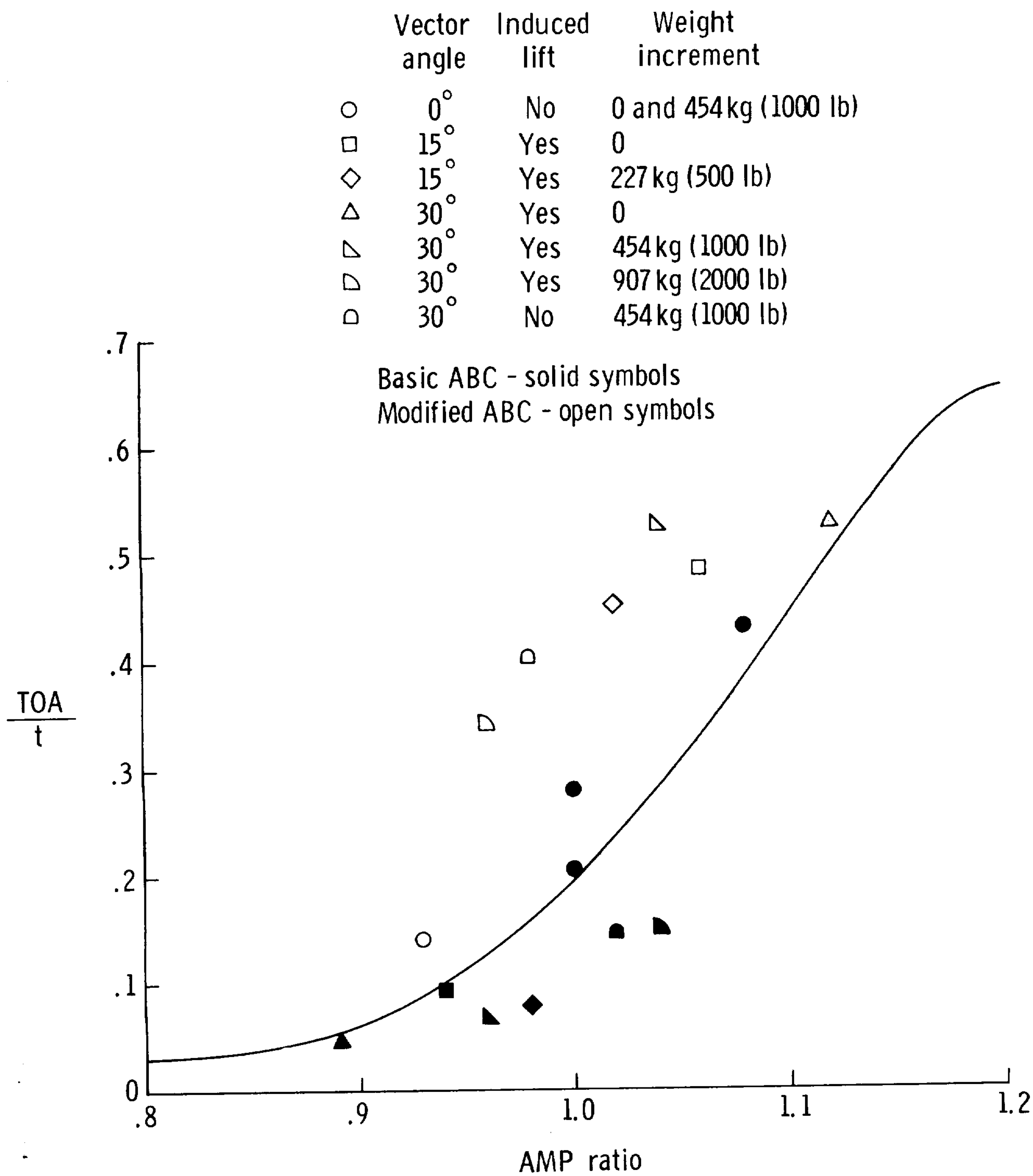

Figure 10.- Aircraft maneuvering parameter.

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